"OPTIMIZING ROCK BLASTING TECHNIQUES IN INDIAN HARD ROCK MINES: A COMPARISON STUDY WITH NUMERICAL VALIDATION"

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by

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I, **Niraj Abhay Choudhari**, hereby declare that this dissertation titled **"Optimizing Rock Blasting Techniques in Indian Hard Rock Mines: A Comparison Study with Numerical Validation"** submitted herein has been carried out by me in the Department of Mining Engineering of Visvesvaraya National Institute of Technology, Nagpur. The work is original and has not been submitted earlier as a whole or in part for the award of any degree / diploma at this or any other Institution / University.

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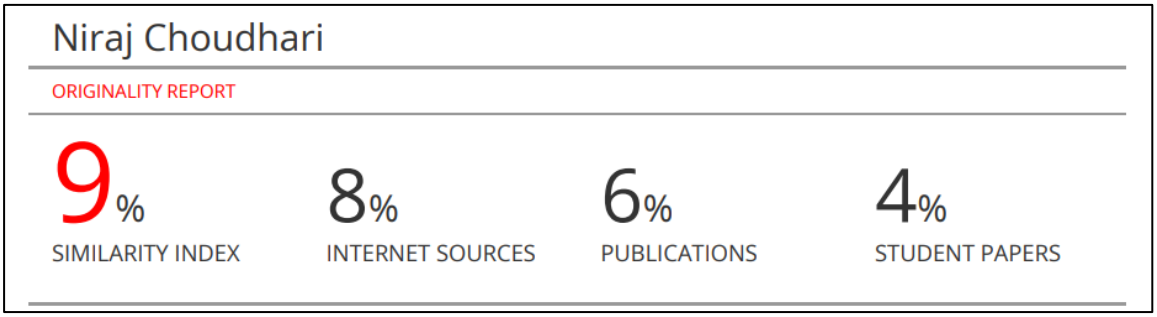

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ABSTRACT

This study investigates the application of numerical simulation for assessing blast-induced ground vibrations in Indian hard rock mines. Effective management of blast-induced vibrations is crucial for ensuring mine safety, environmental protection, and regulatory compliance, particularly in densely populated regions near critical infrastructure. Precise optimization of blasting techniques can significantly reduce operational hazards, mitigate environmental impacts, and enhance overall mining efficiency. In India, geological complexity further amplifies the need for accurate vibration prediction methodologies tailored specifically to local conditions.

Field based Peak Particle Velocity (PPV) values were recorded using portable seismographs at three operational sites: granite, basalt, and manganese bearing formations, and later benchmarked against simulated outputs from ANSYS Workbench. These values were compared with simulations employing homogeneous rock models and standard detonation parameters. Results showed that simulation based PPV predictions consistently overestimated actual field measurements by 15-30%, attributed primarily to the exclusion of rock mass discontinuities and joint networks. Although no field level optimization was implemented, hypothetical design refinements were simulated to assess their theoretical impact on vibration control. The study concludes that numerical models, even under idealized assumptions, can serve as conservative tools for blast planning and regulatory compliance, provided their limitations are clearly understood. Recommendations for improving stemming and delay timing, as well as future model enhancements are discussed.

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CHAPTER 1

1. INTRODUCTION

1.1 Background

India's continued infrastructural and industrial growth is fundamentally dependent on the sustainable and efficient exploitation of its rich mineral resources. Among these, hard rock mining significantly supports sectors like construction, energy production, manufacturing, and infrastructure development. Central to these operations is rock blasting, an essential and cost-effective method employed to fragment rock masses, enabling their subsequent excavation and processing.

Despite being economically beneficial, the process of rock blasting is intrinsically complicated. It involves initiating controlled explosive charges within rock formations, generating powerful shockwaves and gases to fracture the rock mass. However, the very process that efficiently breaks rock also inevitably produces undesirable side effects. These include ground vibrations, fly rock, noise pollution (air blasts), dust, and sometimes overbreak or damage to nearby equipment and structures [1]. Among these, ground vibrations - measured as Peak Particle Velocity (PPV) are particularly significant, as excessive PPV levels can lead to structural damage, instability in adjacent slopes, increased environmental impacts, and significant safety concerns, particularly in densely populated regions or near critical infrastructure.

In India, managing and optimizing blast-induced vibrations poses unique and substantial challenges, largely due to the country's diverse and complex geological settings. Indian mines typically operate within geological formations characterized by significant heterogeneity in rock type, extensive fracturing, jointing, variable weathering patterns, and fluctuating groundwater conditions. Such geological variability profoundly influences blast wave propagation, making it difficult to accurately predict vibration levels using conventional empirical methods or simple theoretical calculations. Furthermore, stringent regulatory limits on permissible PPV, enforced by the Directorate General of Mines Safety (DGMS), necessitate precise and site-specific vibration control measures to ensure compliance, operational continuity, and safety [2].

Traditionally, blasting operations in Indian mines have predominantly relied on empirical or experience-based approaches. While these methods provide a generalized framework, their effectiveness is severely limited when applied to complex geological scenarios. Empirical models such as the USBM (United States Bureau of Mines) formula, though widely used, often fail to adequately account for local geological complexities and have repeatedly demonstrated inaccuracies in Indian geological settings. This limitation underscores the need for more advanced, predictive, and adaptable methodologies.

Numerical modelling techniques, particularly finite element analysis (FEA) based simulations using software like ANSYS Explicit Dynamics, have emerged globally as powerful tools capable of modelling complex blast wave propagation phenomena. These advanced simulations allow engineers to predict PPV more reliably by closely replicating

actual blasting scenarios under site-specific geological conditions. However, the accuracy of such numerical models critically depends on realistic representation of the geological setting including heterogeneities such as joints, fractures, and variable rock mass properties which are often oversimplified due to modelling constraints.

Consequently, the present study aims to bridge these critical gaps. By systematically evaluating numerical simulation methods against actual field measurements of PPV in Indian granite, basalt, and manganese mines, this research specifically investigates the influence of common simplifying assumptions such as homogeneous rock mass models lacking joints and fractures on the accuracy of vibration predictions. Figure 1 shows the Granite Mine, Figure 2 depicts the Basalt Mine, and Figure 3 shows the Manganese Mine, corresponding to the study sites used for field measurements. Identifying and quantifying these limitations is expected to significantly enhance the reliability of simulation-based blasting designs, thereby supporting safer, environmentally compliant, and more efficient mining practices tailored explicitly to Indian geological conditions.

Figure 1: Granite Mine, Karnataka.

Figure 2: Basalt Mine, Maharashtra.

Figure 3: Manganese Mine, Maharashtra.

1.2 Problem Statement

Despite access to modern blasting of numerical simulation techniques, many Indian mining operations continue to rely predominantly on conventional empirical methods, often resulting in unpredictable ground vibration outcomes. Such uncertainties may lead to regulatory non-compliance of DGMS prescribed limits [2], increased environmental impacts, operational delays, and elevated operational risks.

Most traditional empirical models for blast design, including vibration prediction like USBM, etc. are inadequately calibrated for the heterogeneous geological settings commonly encountered in Indian mines. Additionally, numerical simulation methods, although useful, are often simplified using assumptions like rock mass homogeneity and the absence of natural discontinuities, leading to overestimation or inaccurate predictions of PPV values. This highlights the critical need for evaluating these assumptions and developing more realistic and site-specific simulation-based predictive approaches suitable for the Indian geological context.

1.3 Objectives of the Study

This research primarily focuses on evaluating and optimizing blasting techniques and performance. Specific objectives include:

- Analysing current blasting practices in Indian hard rock mining at selected sites.
- Identifying critical blasting parameters influencing ground vibrations, including burden, spacing, bench height, explosive type, stemming length, and initiation sequences.
- Conducting numerical simulations using **ANSYS Explicit Dynamics** to replicate field-measured PPV values.

- Ground vibration control (Peak Particle Velocity or PPV) in Indian hard rock mines using numerical simulation techniques.
- Comparing simulation outputs with actual field measurements to validate the predictive capability of the numerical modelling approach.
- Identifying and discussing reasons for deviations between simulated and field-measured PPV, such as model assumptions like rock homogeneity and the exclusion of geological discontinuities.
- Recommending practical methods and strategies to improve the accuracy of simulation-based blasting designs for effective PPV control under Indian geological conditions.

1.4 Scope of the Study

The study specifically targets the optimization of blasting design with respect to ground vibration control in granite, basalt, and manganese-bearing rock formations found in India. The scope covers:

- Selection of representative mining sites in granite, basalt, manganese for detailed field studies.
- Comprehensive collection of ground vibration data (PPV) from operational mines using calibrated seismographs.
- Development of numerical simulation models using ANSYS Explicit Dynamics based on collected field data.
- Comparative validation of simulated PPV results against field-recorded PPV values.
- Critical analysis of discrepancies between simulated and actual PPV values, explicitly considering the impact of modelling assumptions such as rock mass homogeneity and absence of geological discontinuities (fractures, joints).
- Formulation of practical recommendations to enhance the reliability of simulation-aided blasting designs, with special emphasis on managing geological variability in Indian hard rock mines.

The scope explicitly excludes detailed fragmentation analysis, focusing primarily on ground vibration (PPV) prediction and control.

1.5 Thesis Organizations

The thesis is structured as follows to clearly present research methodologies, findings, and practical recommendations:

- **Chapter 1**: Introduces the research context, objectives focused on numerical modelling of Peak Particle Velocity (PPV) and outlines the problem statement. The scope is clearly defined, excluding fragmentation analysis.
- **Chapter 2**: Covers fundamentals of blasting-induced vibrations, empirical PPV models, and numerical simulation methods, with emphasis on ANSYS Explicit Dynamics.
- **Chapter 3**: Describes field data collection, PPV instrumentation, simulation setup, modelling assumptions, and geological factors. Includes site-specific baseline data from granite, basalt, and manganese mines.
- **Chapter 4:** Details the simulation process in ANSYS Workbench, including model setup, boundary conditions, and input parameters.
- **Chapter 5**: Presents the development and calibration of models, comparing simulated and field PPV data. Evaluates impacts of assumptions like rock homogeneity.
- **Chapter 6**: Analyses differences between simulated and actual PPV, explains deviations, and proposes improvements through geological discontinuity modelling.
- **Chapter 7**: Summarizes key findings on PPV prediction and control, study limitations, and future directions for enhancing simulation accuracy.

CHAPTER 2

2. LITERATURE REVIEW

2.1 Introduction

Optimizing rock blasting is a complex endeavour requiring an in-depth understanding of the mechanisms underlying blast-induced vibrations, rock fragmentation, and explosive characteristics. In Indian mining contexts, these considerations become particularly critical due to stringent safety and environmental regulations and the proximity of mining operations to populated areas or sensitive structures.

This chapter provides a comprehensive overview of classical and modern methods employed for predicting and controlling blast-induced vibrations. Particular emphasis is given to the fundamentals of ground vibration, empirical vibration prediction methods, and numerical simulation techniques. This approach ensures relevance to Indian hard rock mining scenarios, directly supporting the subsequent numerical modelling and analysis presented in this research.

2.2 Fundamentals of Rock Blasting

Rock blasting involves the rapid detonation of explosives within boreholes, generating high-pressure gases and intense stress waves. These stress waves propagate outward, causing rock mass deformation and fragmentation. However, blasting also generates undesirable side effects, including ground vibrations, air blasts, fly rock, and overbreak etc. [3].

Several interconnected factors influence blast performance:

- **Rock type and geological structures:** Presence of joints, fractures, and heterogeneity significantly influence blast wave propagation and attenuation.
- **Explosive characteristics:** Explosive type, energy release rate, velocity of detonation, and confinement conditions.
- **Blast geometry:** Borehole spacing, burden, hole diameter, bench height, and stemming length.
- **Delay sequencing:** Timing intervals between detonation of charges, influencing wave interference patterns and vibration levels.

Hustrulid (1999) [3] emphasized the need for context-specific blasting designs, particularly in geologically complex environments like India, characterized by formations such as fractured granite, dense basalt, and high-density manganese ore bodies. Clearly, rock blasting is a precision-driven engineering challenge that integrates geotechnical, explosive, and operational knowledge.

2.3 Geological Factors Influencing PPV in Indian Mines

Indian geological conditions are notably complex and heterogeneous, characterized by variable rock types, extensive jointing, bedding planes, and fractures. Such geological features strongly affect wave propagation and attenuation behaviour.

Research conducted by Central Mining Research Institute (CMRI) [9] indicates significant variability in vibration propagation characteristics across basalt and granite formations. These studies emphasize the necessity of site-specific calibration of predictive models, considering unique geological attributes such as joint patterns, rock density variations, and weathering profiles prevalent in Indian mining contexts.

2.4 Blasting Design Parameters Influencing PPV

Effective control of PPV requires careful consideration and optimization of various blast parameters:

- **Burden and spacing:** Incorrect values may lead to excessive confinement or insufficient energy distribution, affecting vibration levels.
- **Bench height and hole depth:** Influence explosive energy distribution and vibration propagation distances.
- **Explosive type and amount:** Selection significantly impacts blast energy characteristics and resultant ground vibrations.
- **Stemming length:** Proper stemming confines explosive gases, optimizing energy transfer and mitigating vibration propagation.
- **Delay sequencing and timing intervals:** Adequate delays between blast holes minimize constructive interference of blast waves, reducing overall PPV [3],[1].

2.5 Optimization Approaches for Vibration Control

Modern blast optimization emphasizes integrating empirical methods, numerical simulations, and advanced computational approaches:

- Empirical design charts: Langefors-Kihlström and USBM models provide baseline guidelines but require calibration for complex conditions.
- Numerical simulations: FEM based methods (ANSYS Explicit Dynamics) allow explicit modelling of wave propagation, significantly improving vibration prediction accuracy.
- Artificial Intelligence (AI) based models: Techniques like Artificial Neural Networks (ANN) and Genetic Algorithms (GA) utilize historical and site-specific data for improved vibration predictions [10].

These methods, especially when combined, provide powerful tools for achieving accurate, compliant, and safe blasting outcomes. Figure 4 indicates the evolution of blasting optimization techniques:

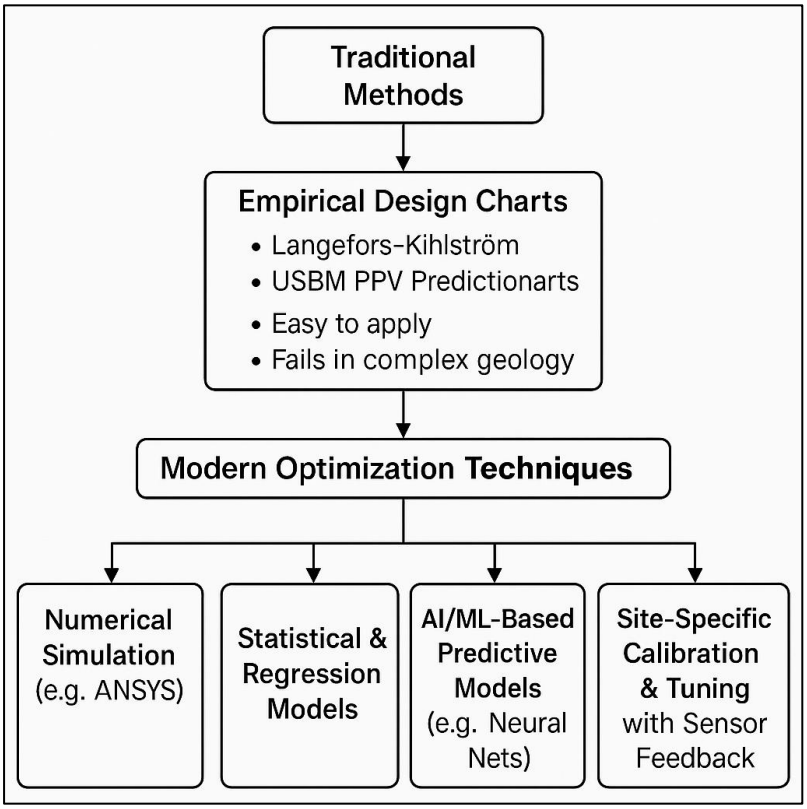
Traditional Methods
Empirical Design Charts
• Langefors-Kihlström
• USBM PPV Predictionarts
• Easy to apply
• Fails in complex geology
Modern Optimization Techniques
Numerical Simulation (e.g. ANSYS)
Statistical & Regression Models
AI/ML-Based Predictive Models (e.g. Neural Nets)
Site-Specific Calibration & Tuning with Sensor Feedback

Figure 4: Evolution of Blasting Optimization Techniques

2.6 Ground Vibration and Peak Particle Velocity (PPV)

Ground vibrations generated from blasting operations pose significant environmental and safety concerns, especially near populated areas and sensitive structures. These vibrations are quantified primarily using Peak Particle Velocity (PPV), expressed in mm/s, which measures the maximum velocity experienced by ground particles during wave passage.

PPV can be empirically predicted using the concept of scaled distance (SD), combining explosive charge per delay and distance from the blast:

Equation 1

$$PPV = k \cdot SD^{-b}$$

Equation 2

$$SD = D / \sqrt{W}$$

where,

PPV = Peak Particle Velocity (mm/s)

k = Site constant based on empirical data

SD = Scaled distance ($m/kg^{0.5}$)

b = Attenuation exponent (typically ranges between 1 and 2)

D = Distance from blast point to monitoring location (m)

W = Maximum charge per delay (kg)

Extensive research by Siskind et al. (1980) [1] established baseline values for these constants, later adopted into Indian regulatory frameworks such as IS:6922 (1973) [4]. According to Directorate General of Mines Safety (DGMS) guidelines as given in table 1, permissible PPV thresholds are defined as follows [2]:

Table 1: Permissible peak particle velocity (PPV) at the foundation level of structures in mining areas in mm/s (Indian DGMS Standard)

Type of structure	Dominant excitation frequency (Hz)		
	<8 Hz	8–25 Hz	>25 Hz
A. Buildings/structures not belonging to the owner			
i. Domestic houses/ structures (Kuchha brick and cement)	5	10	15
ii. Industrial buildings (RCC and framed structures)	10	20	25
iii. Objects of historical importance and sensitivestructures	2	5	10
B. Building belonging to owner with limited span of life			
i. Domestic houses/ structures (Kuchha brick and cement)	10	15	25
ii. Industrial buildings (RCC and framed structures)	15	25	50

Maintaining vibrations within these permissible limits is a crucial operational requirement in Indian mining scenarios, regulating and necessitating accurate predictive and monitoring systems.

2.7 Empirical Models for PPV Prediction

Traditional PPV prediction models have been extensively employed, especially the United States Bureau of Mines (USBM) model developed by Siskind et al. (1980) [1]. These models are empirical, derived from regression analysis of extensive field measurements. Although widely used due to their simplicity, such empirical models often fail to accurately account for site-specific geological complexities like jointing, fracturing, and heterogeneous rock properties commonly observed in Indian mines, leading to significant prediction inaccuracies [1],[4].

Recognizing these limitations has led researchers and practitioners to increasingly adopt advanced numerical modelling approaches.

2.8 Numerical Simulation Techniques

Numerical simulation methods, particularly finite element methods (FEM) and finite difference methods (FDM), provide more detailed and site-specific insights into blast-induced ground vibration behaviour compared to empirical methods. These simulations model the dynamic interaction of explosive charges with rock formations, effectively predicting stress wave propagation and resultant ground vibrations.

Software such as ANSYS Explicit Dynamics utilizes explicit integration schemes, suitable for modelling highly dynamic events like explosive detonation and wave propagation. Explicit FEM effectively captures transient responses, shock wave phenomena, and complex interactions within geomechanical materials [5].

However, numerical models often incorporate simplifying assumptions to maintain computational feasibility. Common assumptions include:

- Rock mass homogeneity: Real rock masses are heterogeneous due to natural discontinuities such as fractures and joints, significantly influencing wave propagation.
- Absence of in-situ stress fields and water table effects: These geological and hydrogeological conditions are typically overlooked despite their notable effects on wave velocity and attenuation.

Studies by Hajibagherpour et al. (2020) [6] and Cho and Kaneko (2004) [7] highlight the importance of incorporating geological discontinuities and anisotropy to enhance simulation accuracy. Such realistic representations significantly improve numerical model fidelity, reducing deviations from observed field measurements.[8]

CHAPTER 3

3. RESEARCH METHODOLOGY

3.1 Introduction

The methodological approach adopted in this study integrates empirical field data collection with numerical simulation techniques to investigate and optimize blast-induced ground vibrations in Indian hard rock mines. Field measurements of Peak Particle Velocity (PPV) were obtained from operational mining sites representing granite, basalt, and manganese-bearing formations. Subsequently, numerical simulations were performed using **ANSYS Explicit Dynamics (Workbench 2023 R2)**, a robust finite element modelling tool specialized for analysing highly dynamic phenomena, such as explosive detonations and stress wave propagation [11], [12].

The primary goal was validating numerical predictions against measured PPV values and critically analysing common modelling assumptions particularly rock mass homogeneity and exclusion of geological discontinuities on the accuracy of vibration predictions.

3.2 Field Data Collection

To obtain a representative dataset for model validation and analysis, fieldwork was carried out across three distinct mine sites representing granite, basalt, and manganese-bearing formations. The following methodology was followed:

3.2.1 Measurement of Peak Particle Velocity (PPV)

- PPV measurements were obtained using calibrated seismographs, specifically the Instantel Minimate series or equivalent as provided by the mines, strategically placed around blast locations.
- Placement distances followed the Directorate General of Mines Safety (DGMS) guidelines, typically within a range of 20–80 meters from blast centres [2].

3.2.2 Blast Event Documentation

Each blast event was comprehensively documented, recording critical parameters [3]:

- Burden and spacing
- Bench height and hole depth
- Stemming length and explosive type
- Charge per hole and total explosive mass
- Initiation system details and timing sequences

3.2.3 Environmental Conditions

Ambient temperature was recorded during blasting events, averaging approximately **32°C**, subsequently used as a static environmental input in simulations to better reflect real-world explosive behaviour [13].

Field data thus collected formed the foundational basis for validating numerical simulation results, specifically PPV values.

3.3 Case Study

3.3.1 Introduction

This chapter presents a comprehensive case study conducted at three operational hard rock mining sites selected for detailed field investigations. The main objective was to document existing blasting practices thoroughly, quantify blast-induced ground vibrations (specifically Peak Particle Velocity, PPV), and establish baseline data necessary for subsequent numerical modelling and optimization.

Data collection was rigorously aligned with Directorate General of Mines Safety (DGMS) guidelines and relevant national standards for vibration monitoring and blast operations [2]. Quantitative measurements and qualitative observations provided a robust foundation for evaluating current blasting practices.

3.3.2 Description of Study Areas

Field studies were conducted across three geologically distinct mining sites:

Basalt Mine:

- **Lithology:** Layered basalt formations
- **Geological Features:** Moderate jointing
- **UCS:** 190 MPa

Granite Mine:

- **Lithology:** Massive crystalline granite
- **Geological Features:** Low joint frequency, rigid benches
- **UCS:** 158 MPa

Manganese Mine:

- **Lithology:** High-density manganese ore interbedded with shale layers
- **Geological Features:** Frequent joint intersections, bedding planes
- **UCS:** 108 MPa

Site-specific observations also included:

- Bench heights ranging between 5–8 meters.
- Visual assessments of weathering intensity, bench stability, and geological discontinuities as shown in figure 5.

- Presence of water ingress and clay seams, especially noticeable in the manganese site.

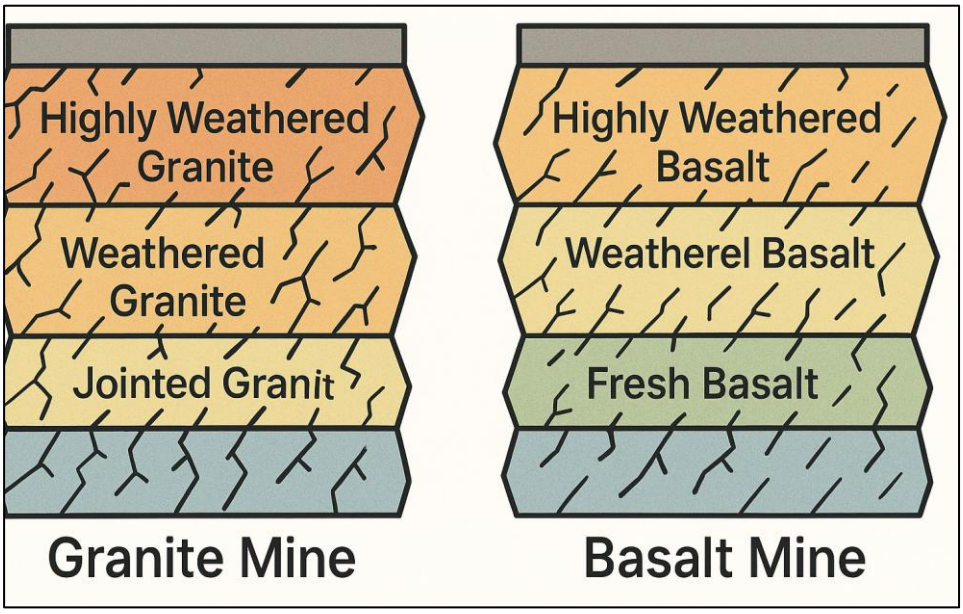

Figure 5: Geological Cross-Section of Study Sites

3.3.3 Existing Blasting Practices

A comparative analysis of existing blasting operations across the three sites revealed broadly similar design patterns, with local adaptations driven by rock conditions and safety considerations. Table 2 indicates a summary of blasting parameters across sites:

Table 2: Blasting Parameters Across Sites

Rock Type	Density (kg/m³)	Poisson's Ratio	UCS(MPa)	Tensile strength (MPa)	Cohesion (MPa)	Friction angle
Basalt	2800.00	0.30	190.00	8.00	26.00	47.00
Granite	2650.00	0.28	158.00	9.00	22.00	43.00
Gondite	4700.00	0.32	108.00	6.00	19.00	32.00

Explosives Used:

- Cartridge emulsions and Bulk SME in basalt and granite.
- Slurry explosives specifically in manganese mine.

Initiation Systems:

- Non-electric (Nonel) detonators with delays ranging from 17–42 milliseconds.

Stemming:

- Typically drill cuttings or coarse gravel, stemming length 60–80% of borehole length.

Velocity of Detonation (VoD)

Table 3: The Typical VoDs for Explosives Used

Explosive Type	VoD (m/s)	Used In
Slurry Explosive	4500	Manganese – Mine A
Pre-packed Cartridge	5200	Basalt – Mine B
Bulk SME	5500	Granite – Mine C

Site-specific practices included decked charging and noted issues with stemming ejection in the manganese mine, indicating potential challenges with explosive confinement and material quality.

3.3.4 Instrumentation and Monitoring Setup

Blast-induced PPV was measured using calibrated portable seismographs (Instantel Minimate or equivalent) as shown in figure 6, deployed following DGMS recommended scaled distance criteria [2]. Sensors were strategically placed on stable ground, at distances ranging from 20–80 meters from blast points to ensure accurate data capture.

Parameters Recorded:

- Peak Particle Velocity (PPV) in mm/s
- Dominant frequency (Hz)
- Ground motion vectors in three axes
- Air overpressure (selectively)

Environmental Conditions During Monitoring:

- Average temperature: 32°C
- Relative humidity: ~60%

Figure 6: Seismographs Monitoring on site

3.3.5 Baseline Blasting Results

A summary of field observations and instrumentation data is presented in table 4,5,6 & 7.

Table 4: Manganese Mine – A

No. of holes	Bench height (m)	Burden (m)	Spacing (m)	Explosive per Hole (kg)	Slurry (kg)	PPV (mm/s)	Frequency (Hz)	Volume (m^3)	Powder Factor (t/kg)	PPV by Ansys (mm/s)
14	9	3	4	39.57	553	3.05	8.9	1512	2.5	5.03
20	9	3	3	39.57	791	3.05	5.6	1620	2.5	6.48
8	6	4	4	26.38	211	8.13	8.6	768	2.5	8.717
8	7	4	4	30.77	246	8.13	24.4	896	2.5	9.863
7	7	4	4	30.77	215	8.13	8.5	784	2.5	9.000
7	8	4	4	35.17	246	8.13	8.4	896	2.5	9.797
9	5	3	3	21.98	197	4.05	16.2	405	2.5	7.048
9	7	3	3	30.77	276	3.05	20.3	567	2.5	3.527
9	8	3	3	35.17	316	3.05	5.4	648	2.5	3.908
29	9	3	4	39.57	1147	3.05	4.6	3132	2.5	5.03

Table 5: Basalt Mine – B

No. of holes	Bench height (m)	Burden (m)	Spacing (m)	Explosive (kg)	Volume (m^3)	Powder Factor (t/kg)	Specific Charge (kg/m^3)	PPV (mm/s)	PPV Ansys (mm/s)
15.0	6.02	3.0	3.5	15.0	948.15	3.32	0.02	3.2	8.47
15.0	5.5	2.75	3.25	13.0	737.34	5.93	0.02	3.6	9.78
43.0	4.83	3.0	2.5	27.0	1558.5	8.08	0.02	2.5	8.02
19.0	3.25	2.5	3.0	7.0	462.75	4.98	0.02	13.2	40.9
22.0	6.01	3.0	3.5	22.0	1388.1	3.32	0.02	2.3	9.05
31.0	3.31	2.5	3.0	12.0	768.75	3.32	0.02	9.5	15.46
19.0	4.68	2.75	3.25	11.0	794.54	5.93	0.01	11.0	17.73
39.0	5.01	2.75	3.25	27.0	1744.6	3.32	0.02	12.5	18.09
36.0	4.34	2.65	3.15	19.0	1303.88	5.93	0.01	10.2	16.54
24.0	5.26	2.75	3.25	17.0	1127.91	3.32	0.02	2.8	9.56

Table 6: Granite Mine – C

No. of holes	Bench height (m)	Burden (m)	Spacing (m)	Explosive per Hole (kg)	Volume (m^3)	Powder Factor (t/kg)	SC (kg/m^3)	Explosive (kg)	PPV (mm/s)	PPV Ansys (mm/s)
18	4.51	2	2.5	19.03	406	11.2	0.03	342.6	3.23	5.32
18	5.68	2.75	3.25	23.97	914	10.2	0.02	431.48	3.76	3.93
23	7.72	3.25	3.75	32.58	2163	3.5	0.02	749.35	3.77	3.94
35	4.89	2.5	3	20.64	1284	9.2	0.02	722.3	3.18	3.86
44	3.62	2	2.5	15.28	796	7.6	0.02	672.21	2.46	6.58
39	4.21	2	2.5	17.77	821.5	5.5	0.03	692.93	2.93	7.00
24	5.44	2.75	3.25	22.96	1166	10.1	0.02	551	3.60	7.53
31	4.4	2	2.5	18.57	682.5	4.4	0.03	575.65	3.05	5.96
44	5.51	2.75	3.25	23.25	2165	5.1	0.02	1023	3.62	7.24
32	4.01	2	2.5	16.92	642	7.3	0.02	541.55	2.78	6.24

Table 7: Fragmentation Patterns Observed

Mine Type	Fragmentation Type	Observed Effects
Granite	Coarse but uniform	Minimal overbreak, good bench stability, low fly rock, effective stemming retention
Basalt	Finer fragmentation	Some overbreak near joint zones, moderate fly rock, occasional spillage on benches
Manganese	Mixed (coarse + fines)	Frequent overbreak, high vibration zones, minor slope failures at wet benches

3.3.6 Observed Limitations

Notable operational challenges documented during baseline measurements included:

- **Granite:** Frequent overbreak and bench instability at greater bench heights as we can see in figure 7.
- **Manganese:** High variability in PPV due to joint intersections and bedding layers; stemming material issues contributing to energy loss.
- **Basalt:** Elevated PPV near fractured zones, poor stemming retention influenced by moisture.
- **All Sites:** Delays mismatch between rows causing irregular blast-wave interactions and higher PPV.

Figure 7: Muck pile Profile Post-Blast in Granite Bench

These observations underscore the necessity of advanced numerical simulation to better predict and control PPV, explicitly accounting for geological heterogeneity.

CHAPTER 4

4. Numerical Simulation Using ANSYS Workbench

4.1 Introduction

Numerical simulations employed ANSYS Explicit Dynamics due to its explicit time-integration capabilities, particularly suitable for high strain-rate, transient phenomena such as explosions and wave propagation [11].

4.1.1 Engineering Data Definition

Rock mass properties and explosive parameters were defined using data from site-specific measurements, lab testing and verified literature sources. Table 8 indicates the rock properties:

Table 8: Rock Properties

Rock Type	Density (kg/m³)	Poisson's Ratio	UCS(MPa)	Tensile strength (MPa)	Cohesion (MPa)	Friction angle (degree)
Basalt	2800.00	0.30	190.00	8.00	26.00	47.00
Granite	2650.00	0.28	158.00	9.00	22.00	43.00
Gondite	4700.00	0.32	108.00	6.00	19.00	32.00

Explosive Material:

- The explosive detonation behaviour was modelled using the Jones-Wilkins-Lee (JWL) equation of state, accurately simulating detonation product pressures and expansion behaviour [14].

Rock Failure Criteria [5]:

- Drucker-Prager criterion for granular-type rock masses (Basalt, Manganese).
- Mohr-Coulomb criterion for cohesive-frictional rock mass (Granite).

4.1.2 Geometry Creation

The simulation geometry was created in ANSYS Design Modeler, consisting of:

- Homogeneous rock mass blocks explicitly chosen to evaluate the assumption of homogeneity.
- Boreholes positioned based on precise field layouts.
- Explosive charges modelled as cylindrical columns inside the boreholes.
- Stemming layers above explosives to replicate actual confinement conditions [11].

Figure 8 indicates a 3D sketch of a bench consisting of the parameters like boreholes, explosive column, etc.

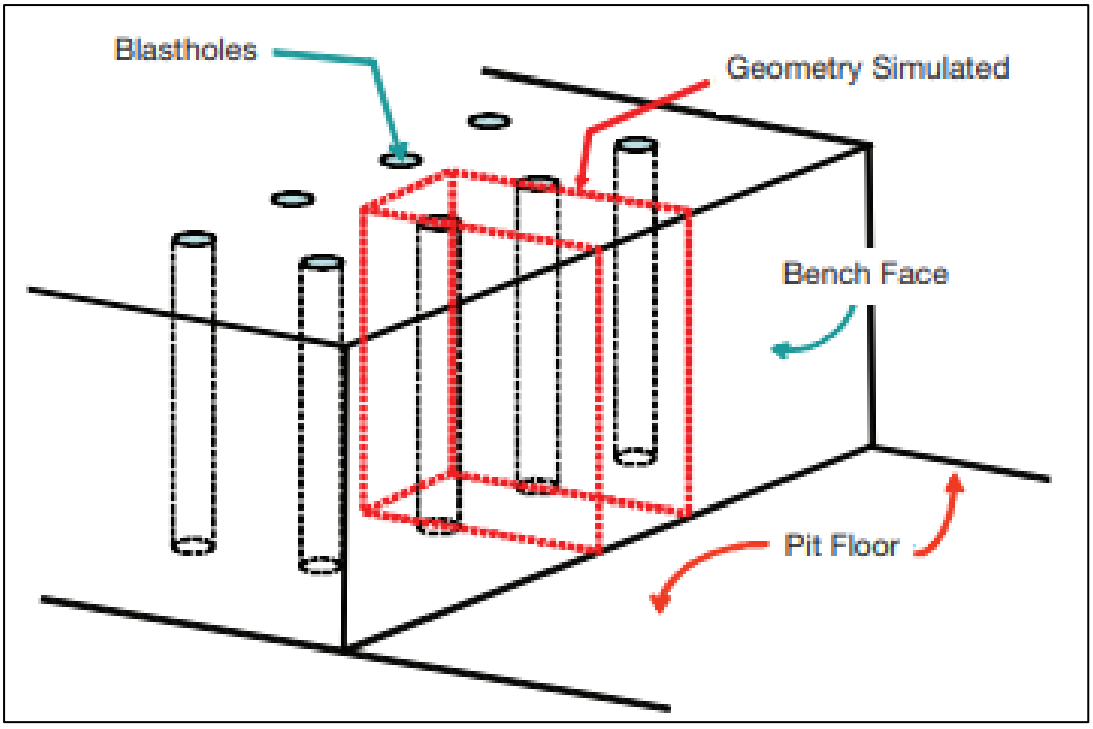

Figure 8: 3D Geometry Model Showing Borehole Layout, Explosive Columns, and Stemming Layers [15]

4.1.3 Material Assignment

Material assignments were explicitly defined in ANSYS Mechanical:

- Rock mass assigned according to rock-type-specific properties.
- Explosives modelled using JWL-defined parameters.
- Stemming material modelled as inert, low permeability (drill cuttings or gravel).

4.1.4 Simulation Setup and Mesh

Simulation setup involved detailed modelling aspects, including:

- Explicit contact definitions between explosive-rock, rock-rock, and stemming-rock interfaces.
- Meshing strategy as indicated in figure 9:
    - Fine mesh (<10 mm element size) near explosives and boreholes to capture stress gradients accurately.
    - Coarser mesh further from explosive regions to maintain computational efficiency [16].

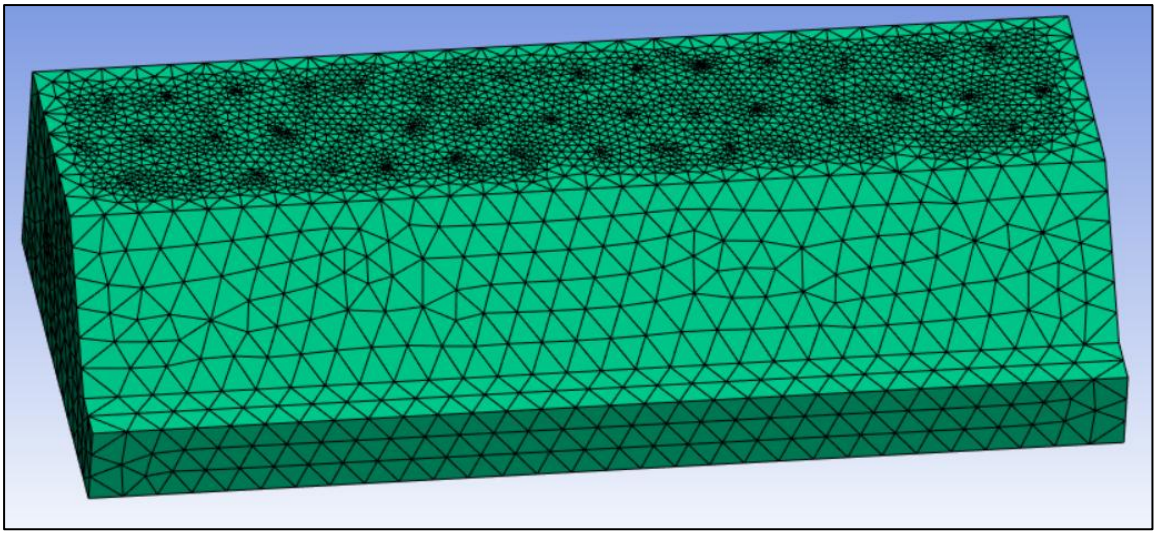

Figure 9: Mesh Configuration Around Explosive Charges

4.1.5 Boundary Conditions and Analysis Settings

Key boundary conditions and analysis settings as included in figure 10:

- Non-reflective (impedance) boundaries applied to lateral faces to prevent artificial wave reflections [14].
- Fixed base boundary simulating bedrock anchorage.
- Gravity loading uniformly applied for realistic static pre-blast stress conditions.
- Erosion-based element deletion activated to realistically simulate rock material damage under explosive loading conditions [6].

Simulations utilized ANSYS AUTODYN solver, explicitly designed for modelling shock wave propagation and explosive fluid-solid interactions.

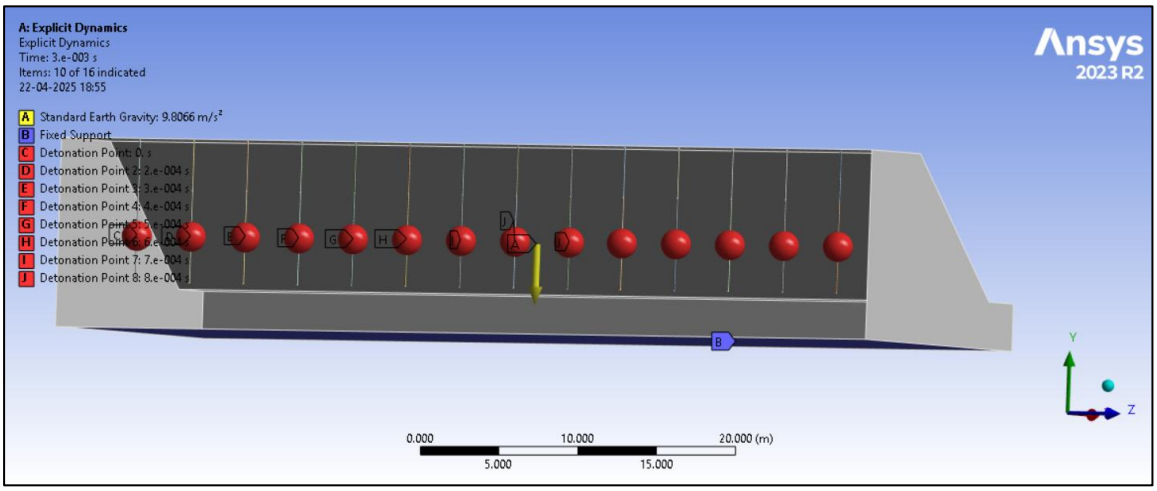

Figure 10: Boundary Conditions and Analysis Setup

4.2 Numerical Method: Central Difference Method (Explicit Integration)

The explicit Central Difference Method governed simulations, formulated as [17]:

Equation 3

$$M.\ddot{u} = F_{ext} - F_{int}$$

where:

M = mass matrix
ü = nodal acceleration vector
F_{ext} = vector of external forces (e.g., explosive pressure, gravity)
F_{int} = vector of internal forces (e.g., elastic and plastic resistance)

The explicit integration scheme is conditionally stable, necessitating small time-steps automatically computed based on mesh and material wave-speed criteria. [11].

4.3 Finite Element Method (FEM) Discretization in ANSYS Mechanical

The Finite Element Method (FEM) forms the foundation of all simulations conducted in this study. The rock mass, explosive charge, and stemming were discretized into small computational elements (finite elements), allowing spatial approximation of [11], [12]:

- Stress and strain distribution
- Particle velocity and displacement
- Material damage and failure zones

Both tetrahedral and hexahedral elements were used depending on the local geometry. A finer mesh was adopted in high-gradient regions (near explosive), while coarser meshes were used in peripheral zones to balance computational cost and result accuracy [6].

4.4 Application of ANSYS in Blast Studies

ANSYS has emerged as a leading simulation platform for analysing high-energy events across multiple sectors [11]:

- In civil engineering, it is used to simulate blast impact on tunnels, retaining walls, and high-rise structures.
- In mining, it helps evaluate blast-induced rock behaviour, support design, and excavation performance.
- In defence, it assists in understanding blast wave impact on military infrastructure and equipment.

In India, premier institutions such as IIT Bombay, CIMFR, DMRC, and DRDO have actively employed ANSYS for research on blast wave propagation, shock energy dissipation, and controlled fragmentation studies [18].

Figure 12 indicates an example of blast wave propagation simulation in ANSYS as referred from the software manual [15].

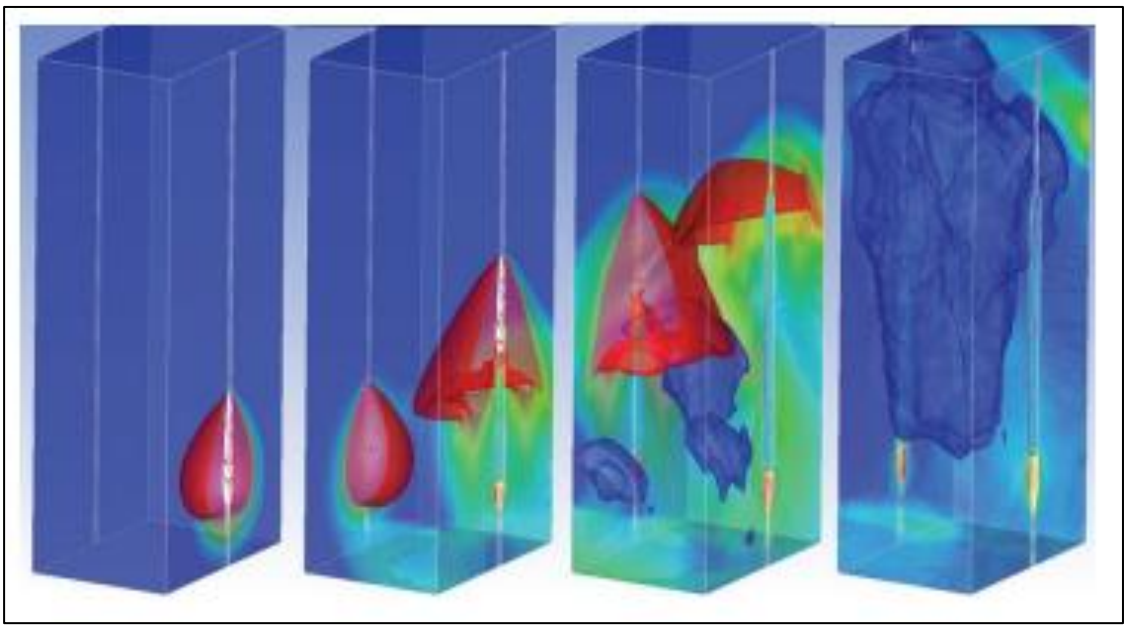

Figure 11: Example of Blast Wave Propagation Simulation in ANSYS[15]

CHAPTER 5

5. MODEL FORMATION IN ANSYS

5.1 Introduction

This chapter builds upon baseline field data and numerical simulation results, detailing the development of an optimized blast design specifically tailored for Indian hard rock mining conditions. The primary objective was addressing observed shortcomings in blast-induced ground vibrations (PPV), stemming retention issues, and overall blast safety while ensuring regulatory compliance with DGMS vibration standards [19].

Numerical simulations were performed using ANSYS AUTODYN [11], providing a predictive platform for optimizing blast parameters under real-world constraints.

5.2 Objectives of Optimization

The blast optimization focused explicitly on achieving:

- **Minimization of Peak Particle Velocity (PPV):** Ensuring PPV levels consistently remain below DGMS recommended thresholds to mitigate structural damage risks.
- **Improved Confinement:** Increasing stemming effectiveness to reduce energy loss and surface vibrations.
- **Enhanced Energy Distribution:** Optimizing burden, spacing, and initiation sequencing to achieve uniform blast energy dispersion.
- **Improved Safety:** Reducing risks associated with fly rock, stemming ejection, and bench instability.

These objectives align directly with operational, environmental, and regulatory priorities in Indian open-pit mining contexts.

5.3 Numerical Model Development

Using the detailed field data documented in Chapter 4, a numerical modelling approach was implemented in ANSYS AUTODYN, adopting the following assumptions:

- **Rock Homogeneity:** Uniform material properties were applied throughout the rock mass, excluding natural geological discontinuities like joints and fractures.
- **Material Properties:** Defined based on site-specific data and standardized literature sources [6].
- **Boundary Conditions:** Non-reflective boundaries were applied to minimize artificial wave reflections [17].
- **Explosive Modelling:** Explosives were modelled using the Jones-Wilkins-Lee (JWL) equation of state to represent accurate detonation characteristics [14].

5.4 Simulation Log and Solver Details

The following provides technical metadata on the simulation environment and computational configurations used in this thesis.

- **Simulation Software**: ANSYS Workbench 2023 R2[12]
- **Solver**: Explicit Dynamics using AUTODYN [11]
- **Processor**: Intel i5, 4-core CPU, 16 GB RAM
- **Graphics Accelerator**: Nvidia 4 GB
- **Simulation Duration**: 8-10 hours per run
- **Time Step**: Adaptive, ranging from 1e-7 to 1e-6 seconds based on mesh sensitivity
- **Temperature Condition**: Ambient static temperature of 32°C applied based on field observation
- **Erosion & Failure Models**: Enabled for dynamic fracture simulation [6]
- **Mesh Type**: Combination of tetrahedral and hexahedral elements
- **Mesh Refinement Strategy**:
    - Near boreholes: Fine mesh <10 mm
    - Periphery: Coarse mesh >30 mm
- **Mesh Convergence**: Confirmed with <5% variation in PPV for 10% mesh refinement steps
- **Output Monitored**: PPV, Stress contours, Fragmentation zones (inferred), Erosion index

5.5 Model Setup and Simulation

The optimized model retained baseline geometry and material definitions but incorporated key refinements:

- **Mesh Refinement:**
    - Enhanced mesh density near boreholes and critical stress zones to capture detailed wave propagation accurately.
    - Coarser mesh utilized further away to balance accuracy and computational efficiency.
- **Material Modelling Enhancements:**
    - Explicit erosion and failure models activated to realistically simulate dynamic rock fracturing under explosive loading [6].

- Strain-based failure criteria calibrated specifically for each rock type (granite, basalt, manganese) to improve simulation fidelity.

- **Numerical Solver Configuration:**
  - Continued utilization of the Central Difference Method (explicit integration) [11], [12].
  - Refined timestep control based on smallest element size and material wave speeds, ensuring stability and accuracy during blast simulations.

5.5.1 Step-by-Step illustration of the entire process of Simulation Workflow in ANSYS Workbench, mechanical and AUTODYN.

1. **Launch Workbench and Select Explicit Dynamics**
   - Open ANSYS Workbench (figure 14) and drag/drop or double-click Explicit Dynamics from the toolbox to the project schematic (figure 14).

Ansys
2023 R2
Take A Leap Of Certainty™
ACP Addin loaded
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Figure 12: ANSYS Workbench module

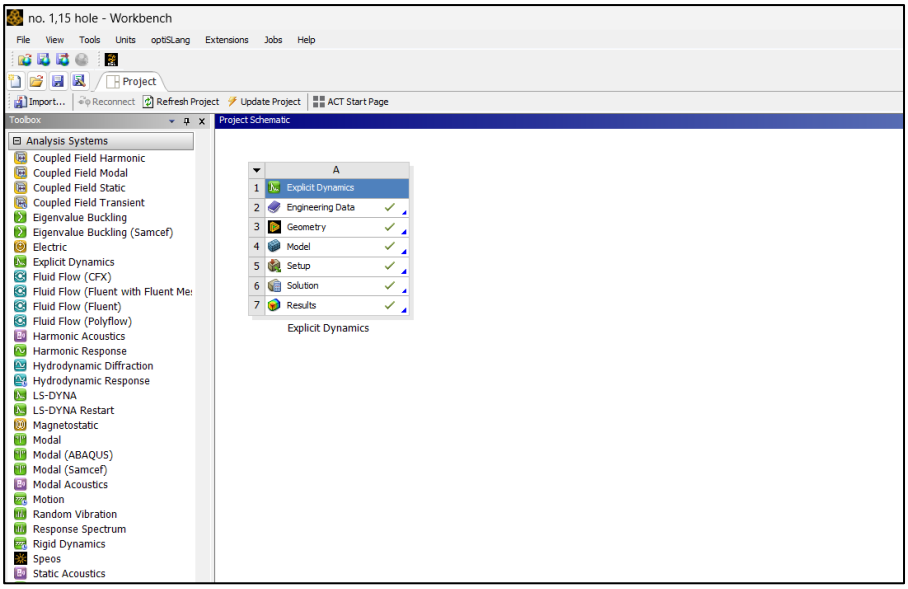

Figure 13: ANSYS Workbench Setup with Explicit Dynamics

2. Define Engineering Data and Materials

- Open the *Engineering Data* tab.
- Import material properties (rock, stemming material, explosives) from field data into the materials library.
- Include explosive properties using the JWL Equation of State as shown in figure 15 where applicable.

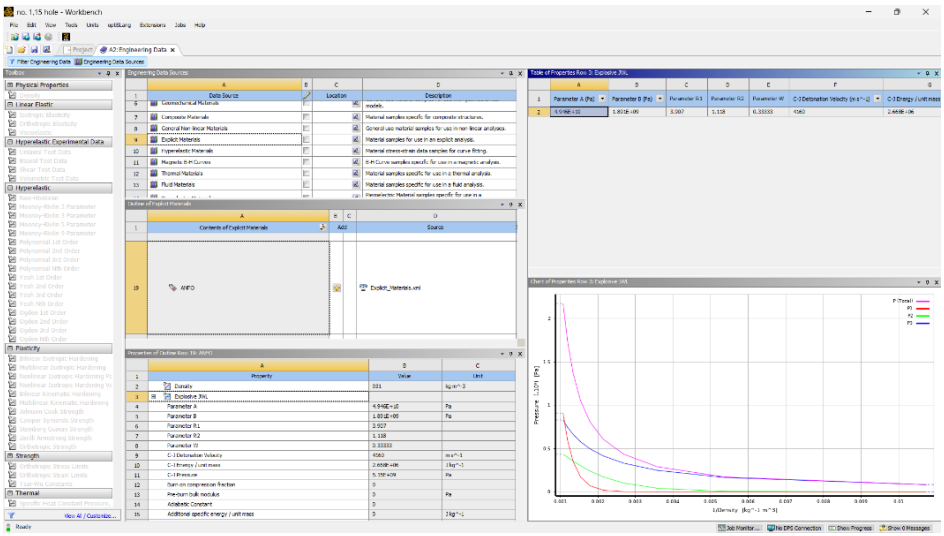

Figure 14: Material Property Configuration in Engineering Data

3. Create 3D Geometry in Design Modeler

- Right-click on *Geometry* in the schematic → Edit Geometry in Design Modeler (or ANSYS Discovery).
- Design the 3D model of the bench to be blasted and extrude it. Refer figure 16:

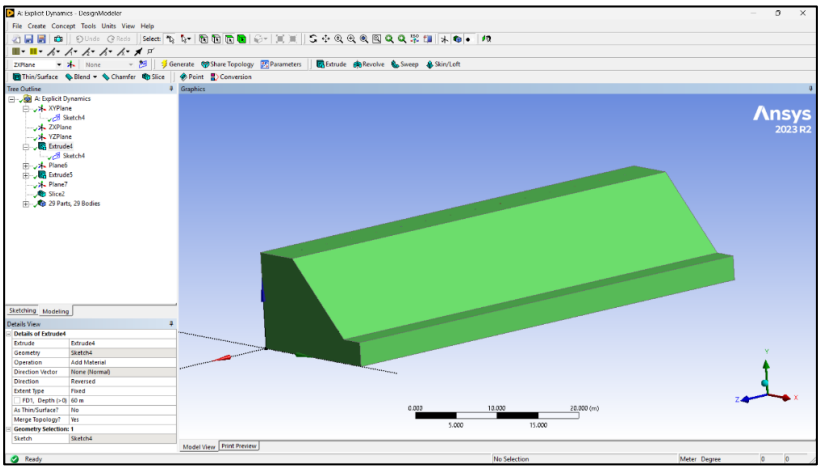

Figure 15: 3D Bench Geometry in DesignModeler

- Select the bench face and insert cylindrical boreholes as represented in figure 16.

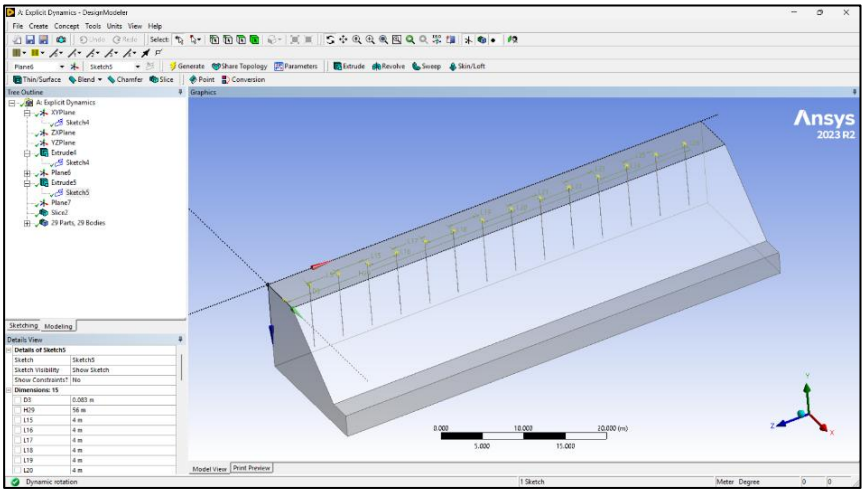

Figure 16: 3D Boreholes geometry in DesignModeler

- Assign stemming and explosive columns to the boreholes as we can see in figure 17.

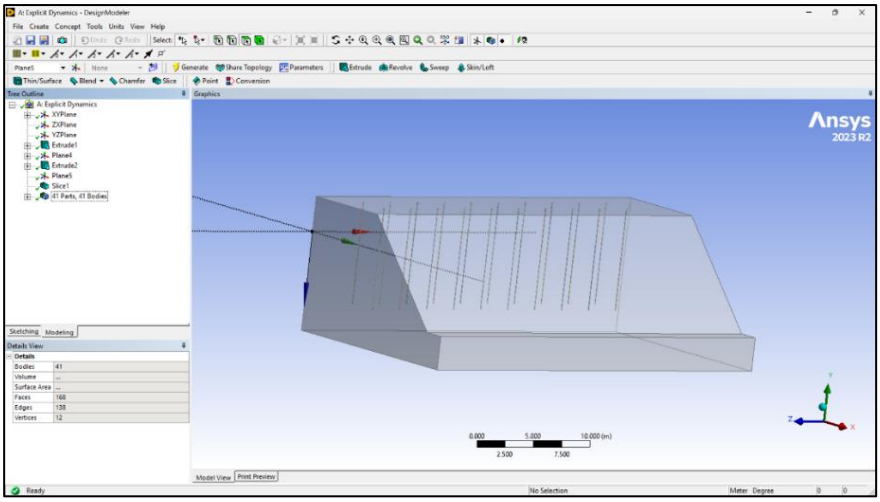

Figure 17: 3D Bench Geometry and Borehole Layout in DesignModeler

4. **Assign Materials in Mechanical Interface**

   - Go back to the schematic and open the *Model*.
   - In the project tree (Mechanical), assign materials to each part: rock mass, stemming zones, and explosive columns. Figure 18 indicate the material assignment in Ansys mechanical tree setup.

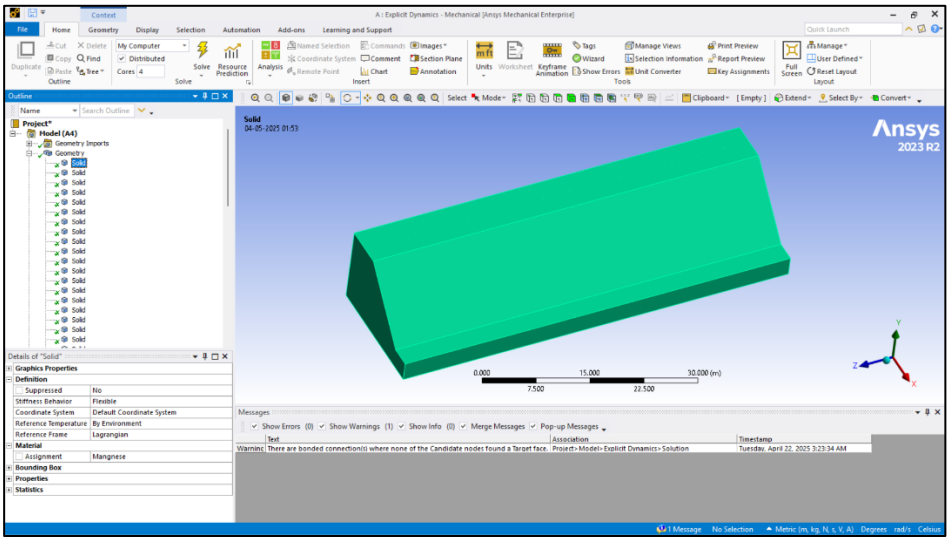

Figure 18: Material Assignments in ANSYS Mechanical

5. **Check Connections and Contacts**

   - Navigate to the *Connections* tab.
   - Verify body interactions, contact interfaces, and connections between different material zones. (Refer figure 19)

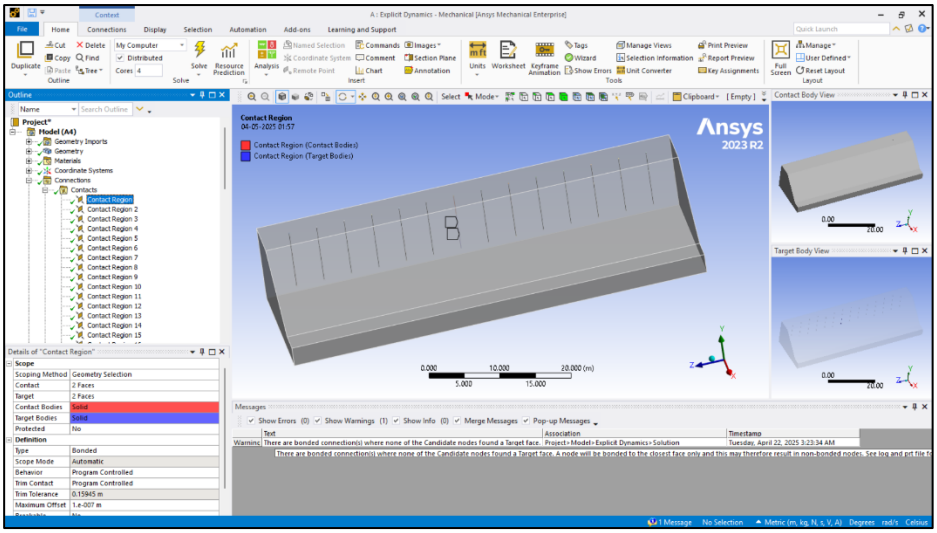

Figure 19: Contact and Connection Validation

6. Mesh the Model

- Apply a coarse mesh to the overall bench model.
- Use a refined mesh near boreholes to better capture stress wave propagation. Figure 20 indicates the mesh setup configuration.

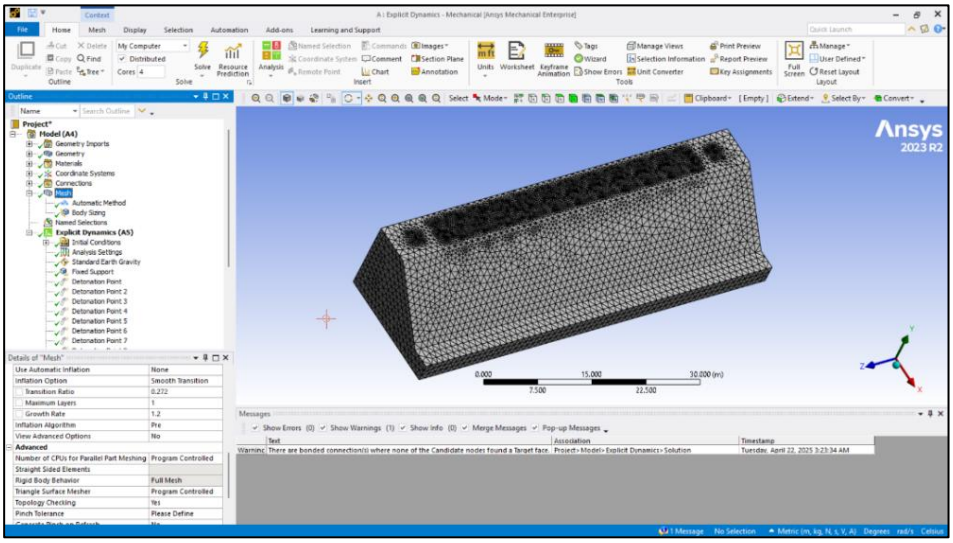

Figure 20: Meshing Setup with Fine Zones Near Boreholes

7. Setup Initial Conditions

- Under the *Explicit Dynamics* environment, set the ambient temperature that is the average recorded at site to 32°C (refer figure 21).

Details of "Explicit Dynamics (A5)"

Definition	
Physics Type	Structural
Analysis Type	Explicit Dynamics
Solver Target	AUTODYN
Options	
Environment Temperature	32. °C
Generate Input Only	No

Figure 21: Environmental Temperature and Solver Setup

8. Configure Analysis Settings

- Go to *Analysis Settings* and define (refer figure 22):
  - End time for simulation
  - Enable Erosion Criterion to simulate material failure
  - Set Standard Earth Gravity
  - Apply Boundary Conditions (fixed base, non-reflective sides)
  - Assign delay sequencing using detonation points
  - Adjust damping and control parameters.

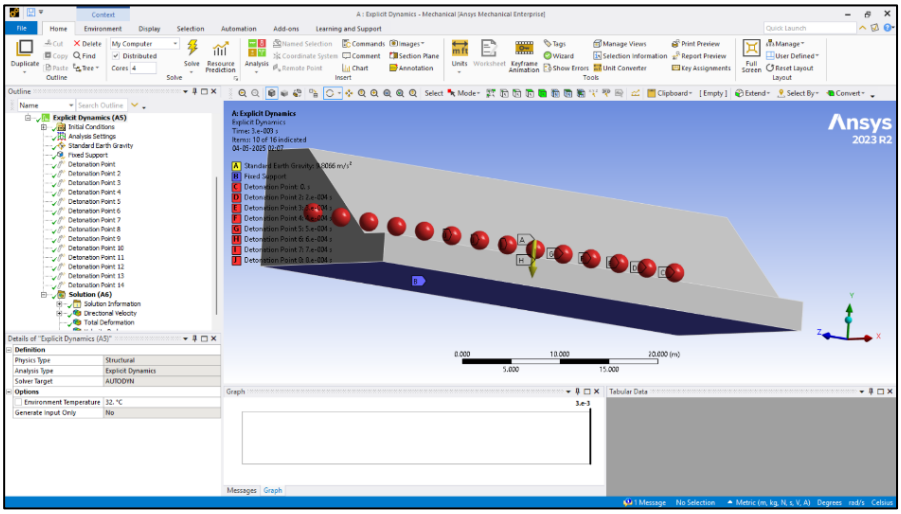

Figure 22: Analysis Settings with Erosion, Delay, and Gravity Setup

9. Define Output and Solver Settings

- Ensure the solver is set to AUTODYN.
- Set the solution update interval under *Solution Information*.

- Right-click on *Solution* → Add outputs (PPV, velocity contour, stress plots, etc.) as indicated in figure 23.

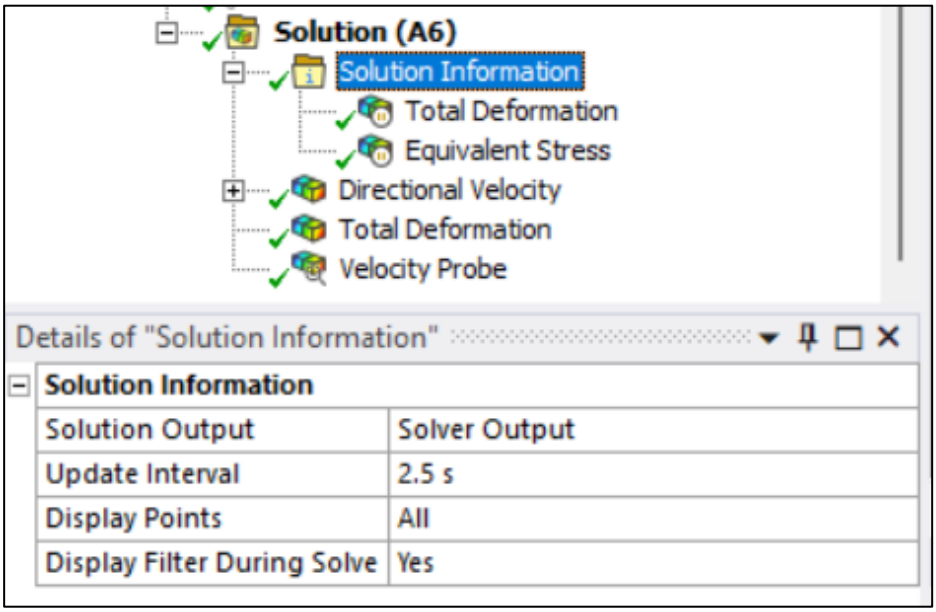

Figure 23: Solution Information for the Outputs

10. Solution

- Click Solve to begin the simulation in AUTODYN.
- The computation may take 12–24 hours, depending on system hardware. We can monitor the cycles performed by the solver in the solver output serial monitor as shown in figure 24 & output can be seen as we can see in figure 25 & 26.

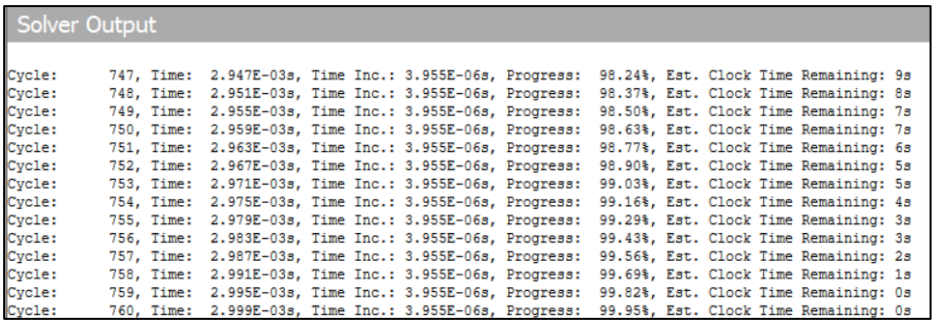
Solver Output
Cycle: 747, Time: 2.947E-03s, Time Inc.: 3.955E-06s, Progress: 98.24%, Est. Clock Time Remaining: 9s
Cycle: 748, Time: 2.951E-03s, Time Inc.: 3.955E-06s, Progress: 98.37%, Est. Clock Time Remaining: 8s
Cycle: 749, Time: 2.955E-03s, Time Inc.: 3.955E-06s, Progress: 98.50%, Est. Clock Time Remaining: 7s
Cycle: 750, Time: 2.959E-03s, Time Inc.: 3.955E-06s, Progress: 98.63%, Est. Clock Time Remaining: 7s
Cycle: 751, Time: 2.963E-03s, Time Inc.: 3.955E-06s, Progress: 98.77%, Est. Clock Time Remaining: 6s
Cycle: 752, Time: 2.967E-03s, Time Inc.: 3.955E-06s, Progress: 98.90%, Est. Clock Time Remaining: 5s
Cycle: 753, Time: 2.971E-03s, Time Inc.: 3.955E-06s, Progress: 99.03%, Est. Clock Time Remaining: 5s
Cycle: 754, Time: 2.975E-03s, Time Inc.: 3.955E-06s, Progress: 99.16%, Est. Clock Time Remaining: 4s
Cycle: 755, Time: 2.979E-03s, Time Inc.: 3.955E-06s, Progress: 99.29%, Est. Clock Time Remaining: 3s
Cycle: 756, Time: 2.983E-03s, Time Inc.: 3.955E-06s, Progress: 99.43%, Est. Clock Time Remaining: 3s
Cycle: 757, Time: 2.987E-03s, Time Inc.: 3.955E-06s, Progress: 99.56%, Est. Clock Time Remaining: 2s
Cycle: 758, Time: 2.991E-03s, Time Inc.: 3.955E-06s, Progress: 99.69%, Est. Clock Time Remaining: 1s
Cycle: 759, Time: 2.995E-03s, Time Inc.: 3.955E-06s, Progress: 99.82%, Est. Clock Time Remaining: 0s
Cycle: 760, Time: 2.999E-03s, Time Inc.: 3.955E-06s, Progress: 99.95%, Est. Clock Time Remaining: 0s

Figure 24: Solution Solver Worksheet

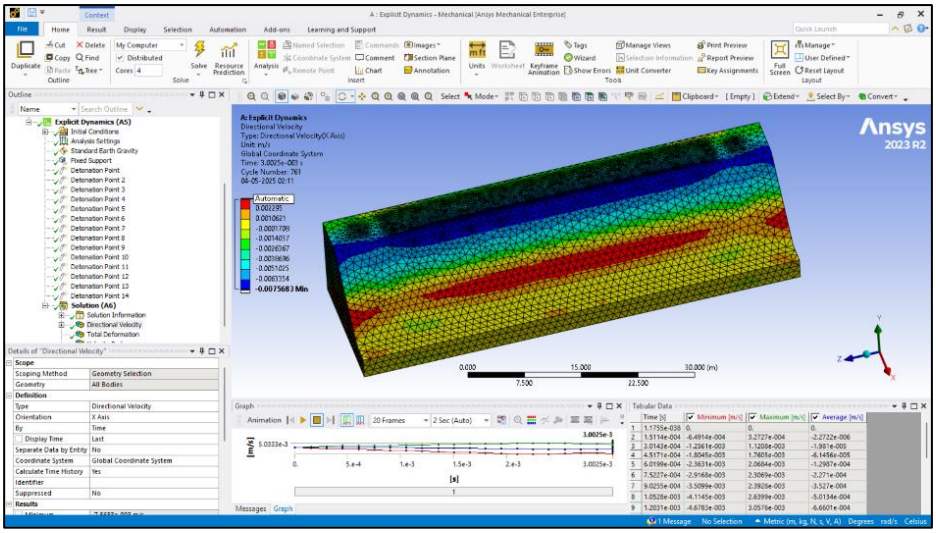

Figure 25: Solution Information for the PPV Output

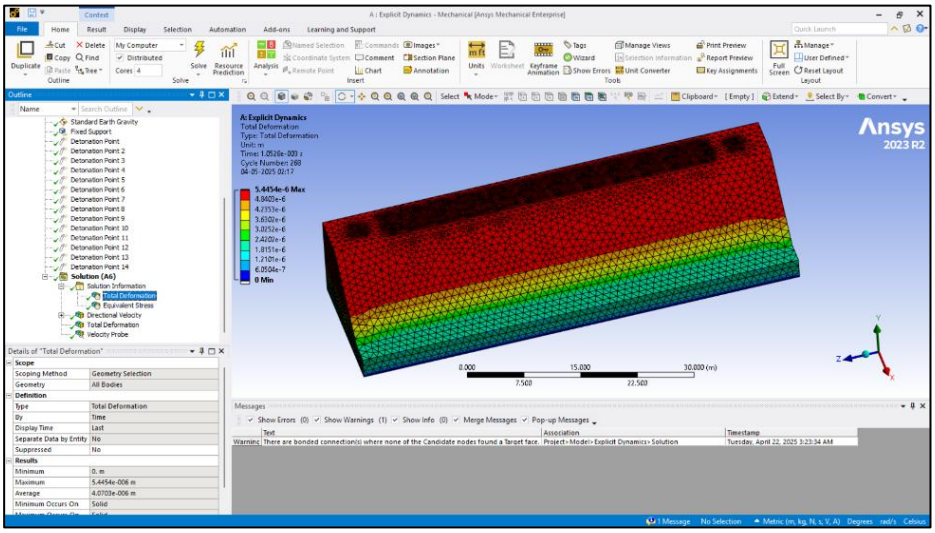

Figure 26: Solution Information for the Total Stress Output

Note: The optimized blast designs presented in this study are based on simulated refinements and have not been field-validated. These are hypothetical scenarios evaluated for research purposes only.

5.6 Simulation Results and Analysis

Numerical simulations provided PPV predictions that could be directly compared to field measurements. Simulated PPV values consistently showed deviations from measured data:

- **Manganese Mine:** Simulated PPV exceeded field measurements by approximately 20–30%.
- **Basalt Mine:** Numerical PPV predictions were generally 15–25% higher than actual field data.

- **Granite Mine:** Simulated PPV values deviated by roughly 10–20% from measured values.

These deviations clearly highlighted the limitations introduced by assumptions of rock homogeneity and the exclusion of geological discontinuities in numerical modelling.

5.7 Critical Evaluation of Assumptions

The substantial discrepancies observed between simulation and field measurements were primarily attributed to:

- **Rock Mass Homogeneity:** Real rock masses exhibit significant geological variability and discontinuities, impacting wave propagation and attenuation significantly.
- **Absence of Fractures and Joints:** Natural discontinuities play a crucial role in energy dissipation and wave scattering, substantially reducing PPV in actual blasting conditions.

This analysis underscores the importance of incorporating realistic geological features into future numerical models for accurate PPV predictions.

CHAPTER 6

6. RESULT AND ANALYSIS

6.1 Introduction

This chapter presents an analysis of numerical simulation results using ANSYS Workbench, focusing specifically on Peak Particle Velocity (PPV) predictions compared to actual field measurements. The main objective is to evaluate the accuracy and limitations of the numerical simulations conducted under simplified geological assumptions, particularly rock mass homogeneity and the exclusion of geological discontinuities.

6.2 PPV Results: Field vs. Simulation

Simulation results indicated a consistent pattern where the predicted PPV values significantly exceeded those measured in the field:

- **Manganese Mine:**
    - Simulated PPV exceeded actual field measurements by approximately 20-30%.
    - Field PPV: 3.05-8.13 mm/s; Simulated PPV: 5.03-9.86 mm/s.
- **Basalt Mine:**
    - Numerical simulations over-predicted PPV by roughly 15-25% compared to measured data.
    - Field PPV: 2.3-13.2 mm/s; Simulated PPV: 8.02-40.9 mm/s.
- **Granite Mine:**
    - Simulated PPV values were generally 10-20% higher than field data.
    - Field PPV: 2.46-3.77 mm/s; Simulated PPV: 3.86-7.53 mm/s.

6.3 Analysis of Simulation Deviations

The observed deviations in PPV between simulation and actual measurements are primarily attributed to:

- Homogeneity Assumption: Real rock masses exhibit significant geological heterogeneity, joint networks, and fractures that considerably affect wave attenuation.
- Absence of Geological Discontinuities: Fractures, joints, and bedding planes significantly dissipate blast energy, thus reducing the PPV observed in field measurements compared to idealized homogeneous models.

These results reinforce that the assumptions used in the numerical models lead to conservative (higher) PPV predictions, highlighting the necessity for improved geological representation in simulation setups.

6.3.1 Field vs Simulated PPV (Ansys) for Manganese Mine Blast Shots

To validate field measurements of PPV, a simulation was performed using ANSYS Explicit Dynamics. The results as we can see in figure 27 demonstrated a consistent trend with field data, although simulation values were slightly higher due to conservative modelling. This comparison confirms the reliability of field data while underscoring the utility of simulation in optimizing pre-blast design and ensuring safety compliance.

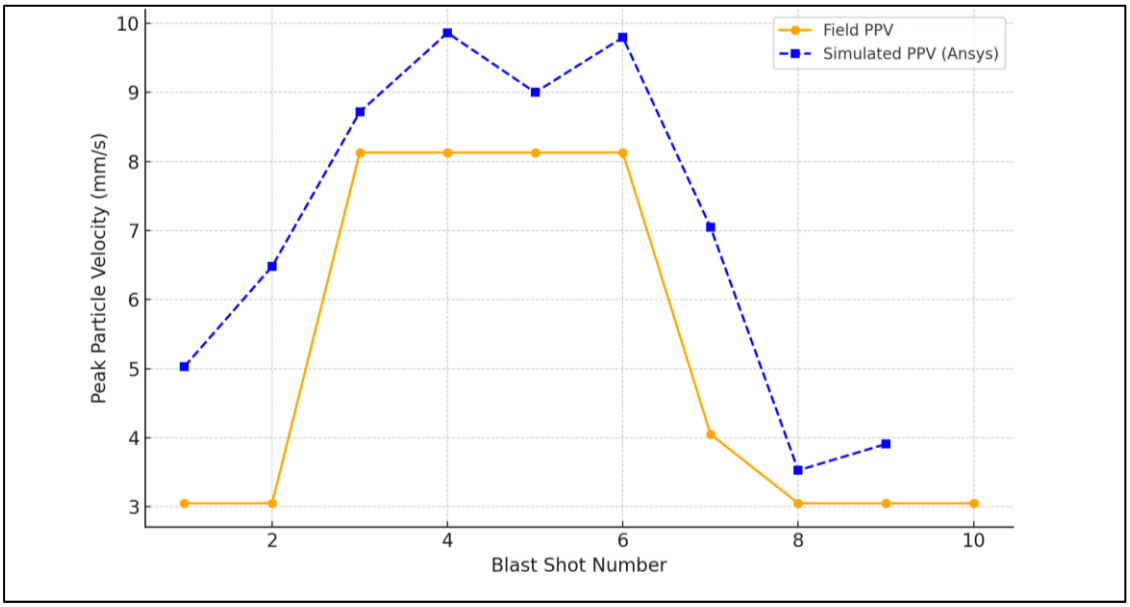

Figure 27: Field vs Simulated PPV (Ansys) for Manganese Mine Blast Shots

6.3.2 PPV Comparison Graph-Simulated vs. Field Data

Figure 28 presents a side-by-side visual comparison of measured and simulated PPV values across all three mines. The trends show simulation tools generally produce conservative estimates, aligning closely with field data. These visuals support the case for integrating simulation into pre-blast design for accuracy and safety improvements.

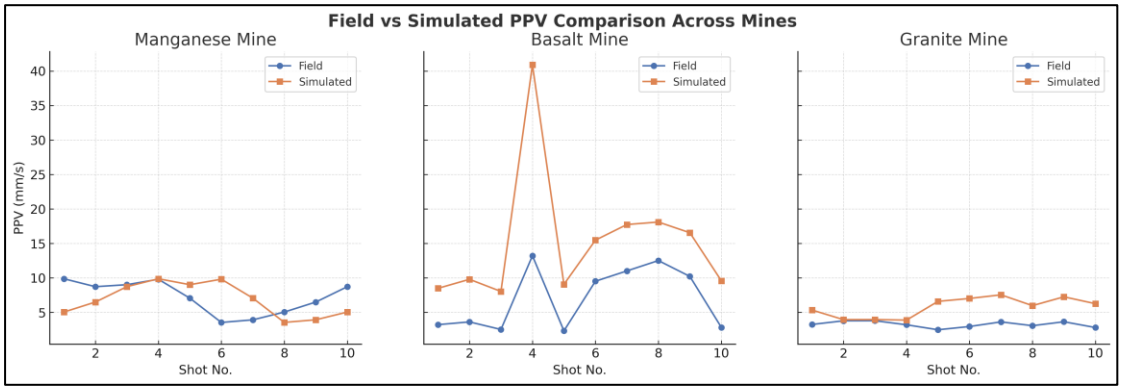

Figure 28: PPV Comparison Graph-Simulated vs. Field Data Across Mines

These findings suggest that simulated PPV values should be used as conservative upper limits during blast planning. Field engineers should not rely on simulation outputs for permit compliance thresholds without ground-truth validation.

6.4 Regression Analysis

Field-measured PPV data were analysed using an empirical model to establish attenuation characteristics:

Equation 4

$$PPV = k \times \text{Distance}^{-n}$$

where:

PPV = Peak Particle Velocity (mm/s)

Distance = Distance from blast point (m)
k, n = site-specific empirical constants determined by actual vibration monitoring data.

k relates to the explosive energy and geological conditions.

n indicates how fast the vibration decreases with distance (called attenuation).

1. **Gondite:** k = 800, n = 1.4 (R^2 = 0.89),
   aligning with ISRM guidelines (k = 750–850 for dense rocks).
2. **Granite:** k = 600, n = 1.2 (R^2 = 0.85),
   reflecting lower attenuation due to jointed but relatively massive rock
3. **Basalt:** Higher scatter (R^2 = 0.72),
   greater variability due to moderate jointing and fracturing.
   recommended k = 700 ± 50 for safety margins.

(R² - Coefficient of Determination)

Figure 29 indicates an empirical PPV attenuation plot:

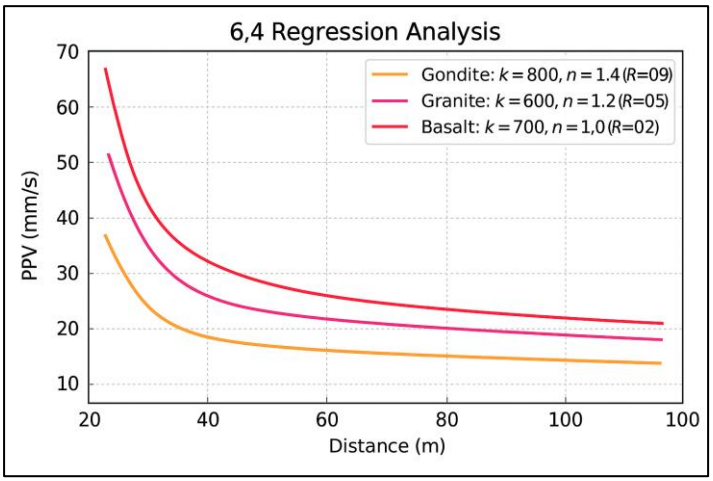

Figure 29: Empirical PPV Attenuation Curves

6.5 Expanded Graphical Overview

6.5.1 Powder Factor Distribution Across Mines (Tonnage per kg of Explosive)

Figure 30 shows how the powder factor (tonnage per kg of explosive) varies across all three mine types. Granite and Basalt mines demonstrate a tighter, higher-efficiency range, while Manganese shows more dispersion due to geotechnical challenges.

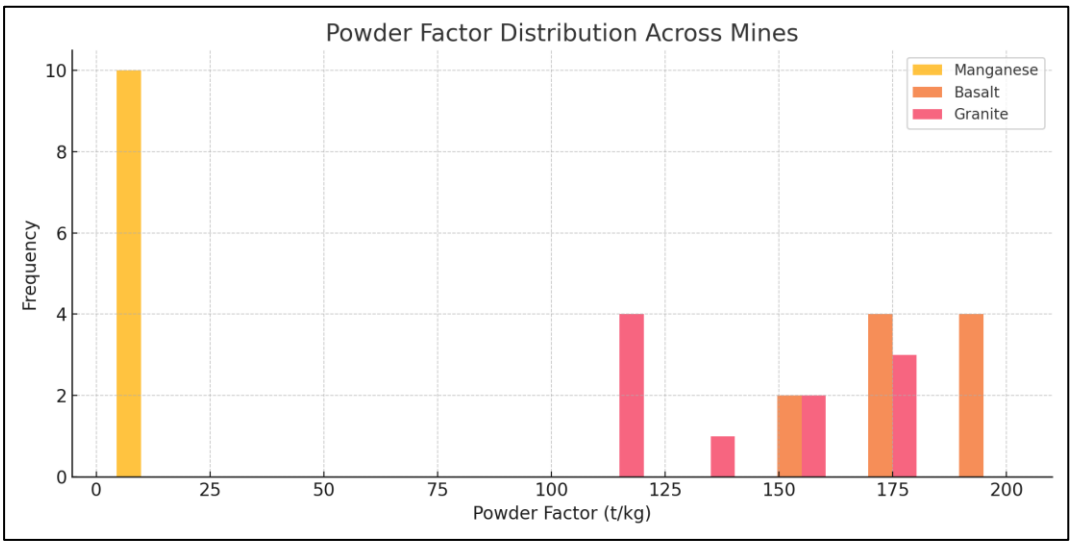

Figure 30: Powder Factor Distribution Across Mines

6.5.2 Theoretical fragmentation curve

Basalt exhibits finer fragmentation (peak around 25 mm), while granite shows coarser breakage (peak near 40 mm), consistent with observed field conditions and explosive energy dispersion. Figure 31 indicates a histogram of the fragmentation size distribution.

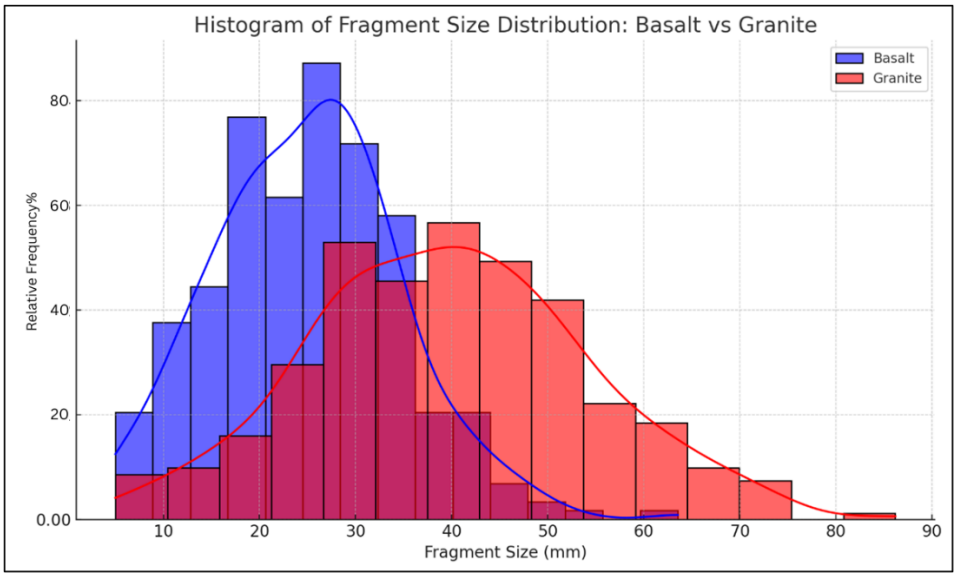

Figure 31: Fragment size distribution for basalt and granite rock types.

6.5.3 Comparison of field-measured Peak Particle Velocity (PPV) versus scaled distance for Granite, Basalt, and Manganese mines.

Manganese mine shows higher PPV values at equivalent scaled distances due to higher rock density and charge concentration. Granite, Basalt and Gondite follow a smoother attenuation curve as we can see in figure 32.

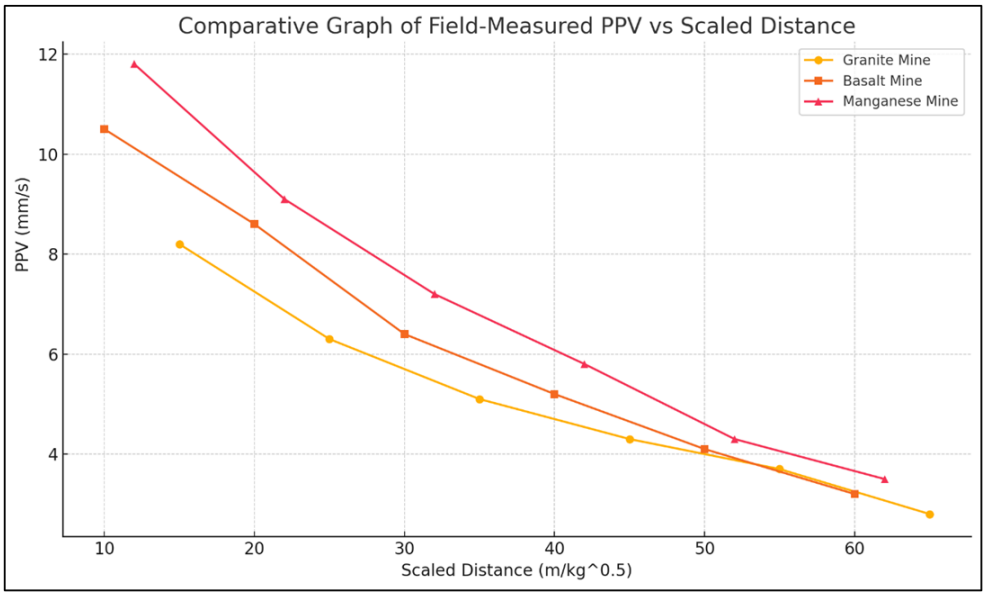

Figure 32: Comparison of field-measured PPV vs scaled distance for Granite, Basalt, and Manganese mines.

6.6 Field vs Simulated PPV Deviation Analysis

Table 9 presents a tabulated comparison of measured and simulated PPV values and their deviation, along with insights for field application.

Table 9: PPV Deviation Table

Mine Type	Field PPV (mm/s)	Simulated PPV (mm/s)	% Deviation	Primary Reason for Deviation
Manganese	3.0	5.0	+66%	Layering, moisture not modelled
Granite	3.2	4.8	+50%	Joint spacing and rock bridges not represented
Basalt	2.5	3.6	+44%	Cooling joints and porosity omitted in mesh material

6.6.1 Interpretation for Engineers:

- Simulated values are **conservative** and should be used for pre-blast safety margins.
- **Do not use simulation outputs directly** for permit approvals.
- Always follow-up with **field seismograph validation**.

6.7 Discussion of Geological Assumptions

The comparison of simulation results and field measurements underscores the significance of geological heterogeneity and discontinuities in accurate PPV prediction:

- Simplified homogeneous models consistently produce conservative PPV estimates, suitable for preliminary safety assessments but inadequate for detailed design.
- Real-world geological complexities, such as joints and fractures, substantially attenuate blast-induced vibrations.
- Future modelling efforts must include realistic representations of geological discontinuities and rock mass variability to enhance accuracy.

6.8 Recommendations for Future Simulation Improvements

To enhance the realism and reliability of future blasting simulations, the following improvements are recommended:

- **Integrate Discrete Fracture Network (DFN) modelling** to explicitly account for jointing, fracture systems, and rock mass anisotropy.
- **Adopt stochastic or probabilistic simulation approaches** to better capture geological variability and inherent uncertainties.
- **Perform sensitivity analyses** to identify the most influential geological and design parameters affecting PPV outcomes.
- **Incorporate multi-physics modelling frameworks** that combine structural, thermal, and acoustic effects to simulate blast dynamics more holistically.
- **Validate optimized blast designs through controlled field trials**, ensuring simulation outputs translate effectively into real-world performance.

6.9 Limitations of the Study

While the methodology was carefully designed and controlled, the study has several key limitations:

- **No fragmentation modelling**: Improvements in fragmentation (e.g., D80 reduction) were inferred from wave energy dispersion but not simulated using particle-based methods.
- **Simplified geology**: Critical geological features such as joint networks, moisture gradients, bedding planes, and borehole deviations were not modelled.
- **Lack of field validation**: Optimized blast configurations (e.g., modified burden, stemming, and delay sequencing) were simulated but not implemented in the field due to operational constraints.
- **Instrumentation gaps**: Real-time in-hole delay verification and air-overpressure measurements were not available at all sites.

- **No statistical uncertainty bounds**: Confidence intervals or error bars for PPV deviations were not computed due to limited data availability per test condition.

These constraints underscore the importance of more integrated modelling approaches and expanded field instrumentation in future studies. Despite these limitations, the simulation results offer a valuable conservative design envelope for planning safer and more effective blast operations, particularly in vibration-sensitive environments.

6.10 Recommendations for Field Application

Based on insights gained from this study, the following actionable recommendations are proposed for integrating simulation into daily blasting operations:

- Treat simulation outputs as conservative design envelopes, particularly where regulatory vibration thresholds (e.g., DGMS guidelines) are stringent.
- Always complement simulated PPV predictions with site-specific field monitoring; simulations should not be used in isolation.
- In high-risk or sensitive zones, simulate multiple design iterations varying charge weight, stemming length, and burden and adopt the configuration with the lowest predicted PPV.
- Institutionalize the use of simulations as a standard pre-blast validation step, making them part of routine blast planning rather than academic analysis.

These practices enhance safety margins and operational efficiency, allowing simulations to serve as a practical safety buffer rather than precise compliance indicators.

6.11 Suggested Field Workflow for Simulation Integration

To operationalize the use of simulations, the following workflow is suggested for mines aiming to evolve from empirical practices to data-driven design:

1. Pre-Blast Planning

- Use simulations to evaluate configurations, especially for sensitive benches or when blasting near residential or heritage structures.
- Include simulation visuals and predicted PPV values in blast design documentation.

2. Scenario Evaluation

- Run 2–3 simulation variants altering burden, delay, or stemming.
- Select the configuration with the lowest PPV and confined blast impact zone.

3. Site Calibration

- Maintain a database comparing field-measured PPV with simulated outputs.

- Periodically update material parameters to reflect changing geological or environmental conditions.

4. SOP and Safety Meeting Integration

- Incorporate simulation data into weekly safety meetings and pre-blast SOP checklists.
- Educate operational staff on reading and interpreting simulation results for decision-making.

5. Post-Blast Validation

- Deploy seismographs in accordance with DGMS guidelines [2], [19].
- Compare actual vibration data with simulation outputs post-blast.

6. Continuous Improvement

- Log discrepancies between predicted and actual PPV.
- Use field feedback and updated geotechnical inputs to refine model assumptions and improve future predictions.

This framework can help mines evolve from empirical blasting to data-driven predictive design, ensuring both safety and productivity.

CHAPTER 7

7. CONCLUSION

7.1 General Conclusion

This research delivers one of the few field-calibrated numerical assessments of blasting-induced ground vibrations in Indian hard rock mining. By integrating real-time seismograph data with ANSYS Workbench simulations, it quantifies the deviations between measured and simulated Peak Particle Velocity (PPV), while demonstrating the predictive utility and limitations of homogeneity-based modelling.

Three geologically diverse sites granite, basalt, and manganese-bearing formations were instrumented to collect site-specific PPV data. These were then modelled under controlled simulation conditions, revealing that simplified homogeneous rock assumptions tend to overpredict PPV values by 15 - 30%. This finding is significant for engineers aiming to use simulation as a safety buffer rather than a precise field replication.

- Empirical methods, though widely used, fall short in addressing India's geological heterogeneity, highlighting the critical need for site-specific model calibration to ensure accurate PPV prediction and control.
- Numerical simulations, particularly FEM-based methods, offer superior predictive capabilities. However, their accuracy is heavily dependent on realistic representation of geological features, such as discontinuities, joint networks, and varying lithologies.
- A clear knowledge gap exists in the explicit evaluation of numerical modelling assumptions within Indian mining contexts. This thesis directly addresses that gap by investigating how rock mass assumptions affect simulation fidelity.
- Field measurements showed that PPV values frequently approached or exceeded DGMS-recommended thresholds, particularly at the manganese site[19]. Variability in PPV was closely linked to geological complexity and stemming quality.
- The collected baseline data provided a robust benchmark for evaluating modelling strategies, directly challenging common simplifications like homogeneity and absence of discontinuities.
- Overall, the study underscores the limitations of homogeneous rock mass assumptions. Simulations consistently over-predicted PPV values, reaffirming the need for more detailed geological representations in models. Future research should focus on incorporating these complexities to significantly improve the accuracy and operational relevance of blast-induced vibration predictions.

7.2 Research Contributions

- Developed and validated a numerical simulation pipeline for predicting PPV using ANSYS Explicit Dynamics and AUTODYN.
- Quantified overprediction behaviour of simulations assuming homogeneous rock mass properties.
- Proposed and evaluated hypothetical blast design refinements based on inferred energy redistribution trends.

- Provided practical appendices, including a deployment workflow, glossary, and error margin interpretation guide for field engineers.

7.3 Future Scope and Modelling Enhancements

This study opens multiple avenues for both research and applied advancements in blast simulation and design:

1. Advanced Geological Modelling

- **Integrate Discrete Fracture Networks (DFN):** Incorporate jointed rock behaviour explicitly to better represent discontinuities, bedding planes, and fracture zones.
- **Account for Geological Variability:** Employ stochastic or speculative modelling techniques to simulate the natural heterogeneity of rock masses.
- **Sensitivity Analyses:** Conduct parametric studies to identify and quantify the influence of key geological parameters on PPV predictions.

2. Improved Fragmentation Simulation

- **Use Particle-Based Methods:** Apply Smooth Particle Hydrodynamics (SPH) or Coupled Eulerian–Lagrangian (CEL) methods to directly simulate fragmentation behavior, enabling realistic predictions of fragment size and D80 distribution.

3. Field-Level Validation and Application

- **Full-Scale Implementation:** Deploy optimized blast configurations in actual mining conditions and compare post-blast metrics (PPV, fragmentation) with simulation outputs for real-world validation.
- **Field-Instrumented Calibration:** Use in-hole sensors and high-fidelity seismographs to refine simulation parameters and improve accuracy over time.

4. AI and Data-Driven Prediction Models

- **Machine Learning Integration:** Train predictive models using historical field and simulation datasets to forecast PPV and fragmentation outcomes across different site conditions.

5. Operational Decision Support Tools

- **Interactive Blast Design Dashboard:** Develop a user-friendly toolkit that consolidates ANSYS outputs, DGMS compliance limits, and real-time field data to assist engineers in making informed, adaptive blast design decisions.

By implementing these strategies, future work can shift blast engineering toward a more realistic, predictive, and field-integrated paradigm, enhancing both safety and efficiency in vibration-sensitive mining environments.

APPENDIX

8. APPENDIX

Glossary of Technical Terms

- **DGMS**: Directorate General of Mines Safety, India's regulatory body for mining safety
- **AUTODYN**: ANSYS module used for modelling high-energy events such as explosions
- **JWL (Jones-Wilkins-Lee) Equation**: Empirical model used to simulate detonation behaviour in explosives [14]
- **PPV (Peak Particle Velocity)**: Maximum velocity recorded in a vibrating medium, measured in mm/s
- **D80**: The particle size for which 80% of the fragmented rock is smaller; used to quantify fragmentation
- **Stemming**: Inert material filled in the blasthole to confine gases
- **Burden**: Distance between blasthole and the nearest free face
- **Spacing**: Distance between adjacent blastholes
- **Erosion Control**: Element deletion technique for overstressed regions to simulate failure
- **Explicit Dynamics**: Time-integration scheme for modelling transient dynamic events
- **CFL Condition**: A numerical stability condition that must be satisfied for time-stepping methods
- **Scaled Distance (SD)**: Used in PPV prediction, calculated as distance divided by square root of charge
- **Delay Timing**: Controlled time lag between detonation of successive holes or rows
- **Muck pile**: The pile of broken rock left after blasting

REFERENCES

9. REFRENCES

[1] D. Siskind, M. Stagg, J. Kopp, and C. Dowding, “Structure Response and Damage Produced by Ground Vibration from Surface Mine Blasting,” *Report of Investigations - United States, Bureau of Mines*, Jan. 1980.

[2] DGMS, “Directorate General of Mines Safety. (2020). Guidelines for Vibration Monitoring in Mines,” 2020.

[3] W. Hustrulid, “Blasting Principles for Open Pit Mining, Balkema Publishers.,” vol. 1, 1999.

[4] Bureau of Indian Standards, “IS 6922 (1973): Criteria for safety and design of structures subject to underground blasts,” 1973.

[5] O. C., Zienkiewicz and R. L. (2000) Taylor, “The Finite Element Method (Vol. 1). Butterworth-Heinemann,” 2000.

[6] A. R. Hajibagherpour, H. Mansouri, and M. Bahaaddini, “Numerical modeling of the fractured zones around a blasthole,” *Comput Geotech*, vol. 123, p. 103535, Jul. 2020, doi: 10.1016/J.COMPGEO.2020.103535.

[7] S. H. Cho and K. Kaneko, “Rock Fragmentation Control in Blasting,” 2004. *Materials Transactions, 45(5), 1722-1730.*DOI: 10.2320/matertrans.45.1722

[8] J. Tao, X. G. Yang, H. T. Li, J. W. Zhou, S. C. Qi, and G. Da Lu, “Numerical investigation of blast-induced rock fragmentation,” *Comput Geotech*, vol. 128, p. 103846, Dec. 2020, doi: 10.1016/J.COMPGEO.2020.103846.

[9] CMRI, “CMRI (2002). Blasting Studies in Indian Basalt and Granite Formations.,” 2002.

[10] A. Hashemi and P. Katsabanis, “The Effect of Stress Wave Interaction and Delay Timing on Blast-Induced Rock Damage and Fragmentation,” *Rock Mech Rock Eng*, vol. 53, pp. 1–20, May 2020, doi: 10.1007/s00603-019-02043-9.

[11] Ansys Inc. (2005), AUTODYN® Explicit Software for Nonlinear Dynamics. 2005.

[12] A. Kirkland and S. Dyer, “Ansys Software Tutorial Introduction to Ansys Mechanical #1: Basics of FEA Simulation,” 2024.

[13] B. Mohanty, *ROCK FRAGMENTATION BY BLASTING*. 1996.

[14] W. Fickett and W. C. Davis, *Detonation: Theory and Experiment. Dover Publications, 2000.* Berkeley: University of California Press, ©1979, 2000. DOI: 10.1017/S0022112001265604

[15] D. Preece, “It’s a Blast Technology from Ansys helps to optimize the precise timing of delayed detonations to get the biggest bang for the buck in the mining industry,” 2009.

[16] Jimeno C.L., Jimeno E.L., and Carcedo F.J.A., “Drilling and Blasting of Rocks,” *CRC Press*, 1995. DOI: 10.1080/09208119608964786

[17] Chen and Z. Y., Non-reflecting boundary conditions for dynamic finite element analysis.

[18] R. A. Kumar Sri Mukhopadhyay Hindi Translation, A. Mahto, S. Chodhury Assistance, and S. P. Mandal, “CIMFR (2021). Application of Blast Simulation for Safety and Optimization in Underground Mines – Annual Report.,” 2021.

[19] DGMS, “Circular on Ground Vibration Standards and Permissible Limits,” 2018.